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ADAPTATION OF THE BLACK OIL SIMULATOR TO TWO-PHASE AND THREE-PHASE RELATIVE PERMEABILITY DETERMINATION USING UNSTEADY-STATE TECHNIQUE

Project BE1, Task 4

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ADAPTATION OF THE BLACK OIL SIMULATOR TO TWO-PHASE AND THREE-PHASE RELATIVE PERMEABILITY MEASUREMENTS USING UNSTEADY STATE TECHNIQUES

BY N. L. Maerefat[1] and R. Parmeswar[1]

ABSTRACT

The development of an unsteady-state procedure for determining three-phase relative permeability curves requires the characterization of the relative permeability curves by adjustable parameters and the adaption of a nonlinear least-squares procedure to the finite-difference approximation of the Buckley-Leverett three-phase flow equation including capillary pressure.

A method was developed to represent three-phase relative permeability data by a functional form based on experimental data. Three-phase relative permeability experimental data reported by previous investigators were represented by relative permeability functions. These functions express the relative permeability of a given phase to all fluid saturations (three saturations in the case of three-phase flow) by a six parameter power law equation. The six parameter equations fit the experimental data within 0.53 percent error.

An automatic method also was developed for representing three-phase relative permeability experimental data. This procedure eliminates errors due to subjective bias.

The developed relative permeability functions were incorporated in a multi-dimensional, three-phase black oil simulator. Also, a finite difference Levenberg-Marquardt routine for solving least-squares problems was adapted to

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Several scientists (1-3)[2] have recognized possible problems when obtaining reliable two-phase unsteady-state (displacement) data from heterogeneous carbonate core samples. Archer and Wong (4) reported that application of the conventional Johnson-Bossler-Naumann (JBN) method (5) for determining relative permeabilities from waterflooding tests could give erroneous results for heterogeneous carbonate as well as for relatively homogeneous porous media having a mixed wettability. Archer and Wong were the first to use a reservoir simulator to interpret laboratory waterflood data. Sigmund and McCaffery (6) in 1979 developed an improved unsteady-state technique to characterize the relative permeability properties of heterogeneous carbonate core samples. Their technique includes capillary pressure effects and expresses relative permeability curves in terms of two adjustable parameters and their standard error estimates. Their procedure provides improved relative permeability data from two-phase displacement for heterogeneous porous media.

In this research, it is intended to extend the Sigmund and McCaffery technique to three-phase flow. To achieve this, three-phase relative permeability curves must be expressed in terms of adjustable parameters and a least-squares technique must be adapted for a three-phase black oil simulator. This report describes what NIPER has done to the present time to achieve these tasks.

DEVELOPMENT OF THREE-PHASE RELATIVE PERMEABILITY PARAMETRIC FUNCTIONS

The relative permeability of each phase (oil,water or gas) is a function of (a) fluid properties (viscosity,IFT, density); (b) rock properties (wettability, pore size distribution, porosity); and (c) saturation of the three phases. However, the fluid and rock properties do not change throughout

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[2]Underlined numbers in parentheses refer to items in the list of references at the end of the report.

TABLE 1

Typical Results from a Three-Phase Relative

Permeability Experiment

RUN	K_{rw}	K_{ro}	K_{rg}	S_w	S_o	S_g
1	23.5	2.4	-	63.0	27.5	9.5
2	25.5	1.7	-	65.5	25.0	9.5
3	4.5	4.8	1.5	31.0	40.0	29.0
4	5.1	4.8	1.1	34.5	39.0	26.5
5	6.5	6.3	0.8	38.0	40.0	22.0
6	6.2	6.4	0.7	37.0	42.0	21.0
7	1.1	20.8	T	22.5	60.5	17.0
8	1.2	25.8	T	20.5	63.0	16.5
9	0.7	8.6	1.2	26.5	46.0	27.5
10	0.6	8.8	1.4	23.2	48.0	28.8
11	0.8	9.2	1.5	27.0	46.5	26.5
12	-	2.6	11.5	16.5	33.5	50.0
13	T	2.7	12.1	18.0	30.5	51.5
14	4.7	5.1	1.6	30.0	40.0	30.0
15	4.8	2.5	1.8	37.0	35.0	28.0
16	7.8	4.8	0.8	40.5	37.0	22.5
17	7.7	5.1	1.1	38.0	39.5	22.5
18	7.8	5.0	1.1	38.5	39.5	22.0
19	1.0	9.8	1.8	20.0	48.5	31.5
20	1.3	9.1	2.0	22.5	47.0	30.5
21	1.3	3.9	5.3	23.0	38.0	39.0
22	1.6	3.7	4.7	26.0	40.5	33.5
23	1.6	4.2	4.6	27.0	40.0	33.0
24	1.1	0.7	15.4	22.0	24.0	54.0
25	1.0	2.2	8.8	23.0	32.0	45.0

-: value could not be measured
T: very small value

The data used to estimate the parameters also contained two-phase oil/water and water/gas data. Therefore, equation 2 can represent one-, two-, and three-phase relative permeability data over the entire range of saturations.

Equation 2 can be written in normalized form as:

$$K_{ri}^{*} = P_{4i}^{*} \, (S_w^{*})^{P_{1i}^{*}} + P_{5i} \, (S_o^{*})^{P_{2i}^{*}} + P_{6i} \, (S_g^{*})^{P_{3i}^{*}} \qquad (3)$$

where

$$K_{ri}^{*} = \frac{K_{ri}}{K_{rimax}} \qquad i = w, o, g$$

$$S_w^{*} = \frac{S_w - (S_w)_{min}}{(S_w)_{max} - (S_w)_{min}}$$

$$S_o^{*} = \frac{S_o - (S_o)_{min}}{(S_o)_{max} - (S_o)_{min}}$$

and

$$S_g^{*} = \frac{S_g - (S_g)_{min}}{(S_g)_{max} - (S_g)_{min}}$$

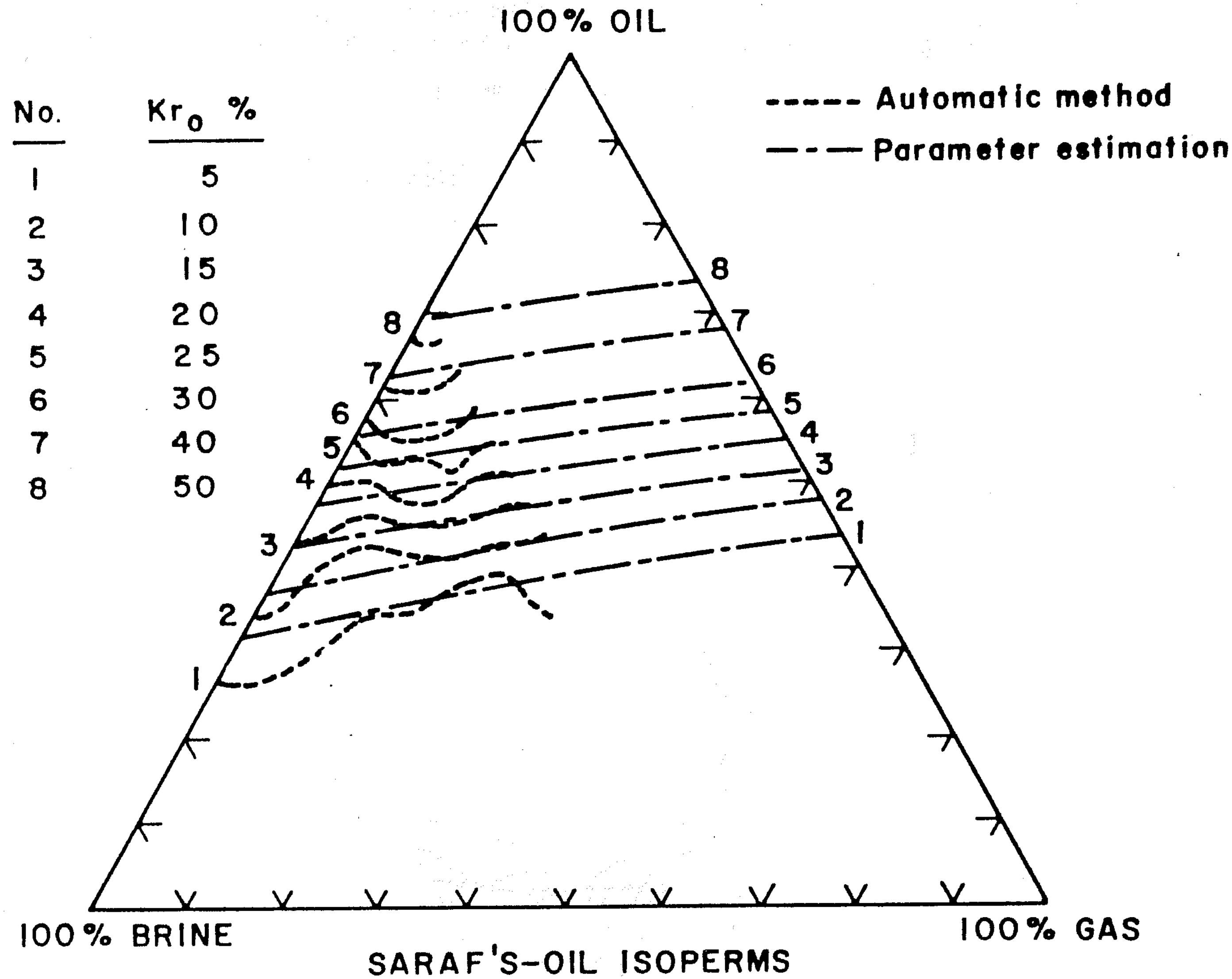

FIGURE 1. - Different representations of three-phase relative permeability data (Saraf's Oil Isoperms).

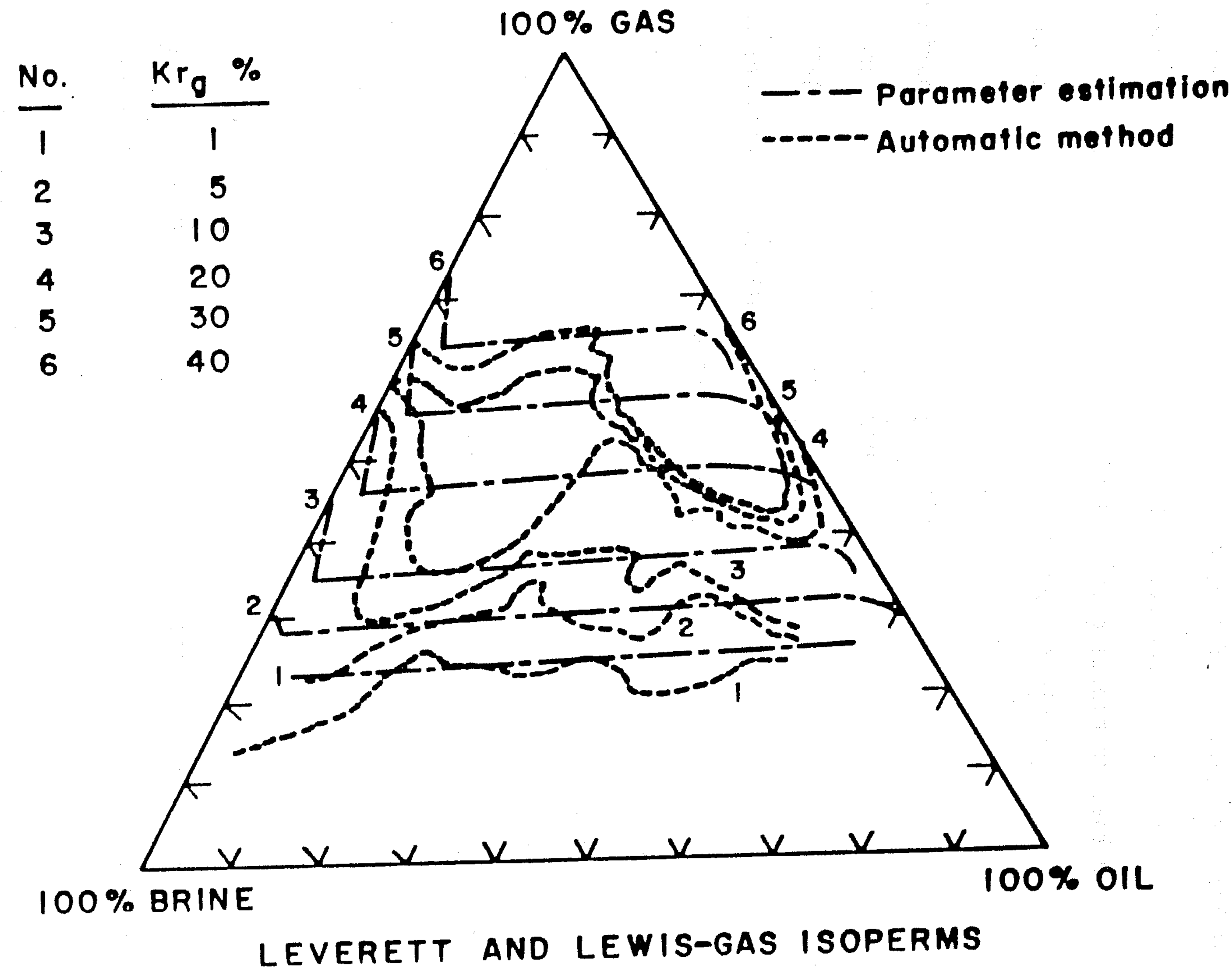

FIGURE 3. - Different representations of three-phase relative permeability data (Leverett and Lewis - Gas Isoperms).

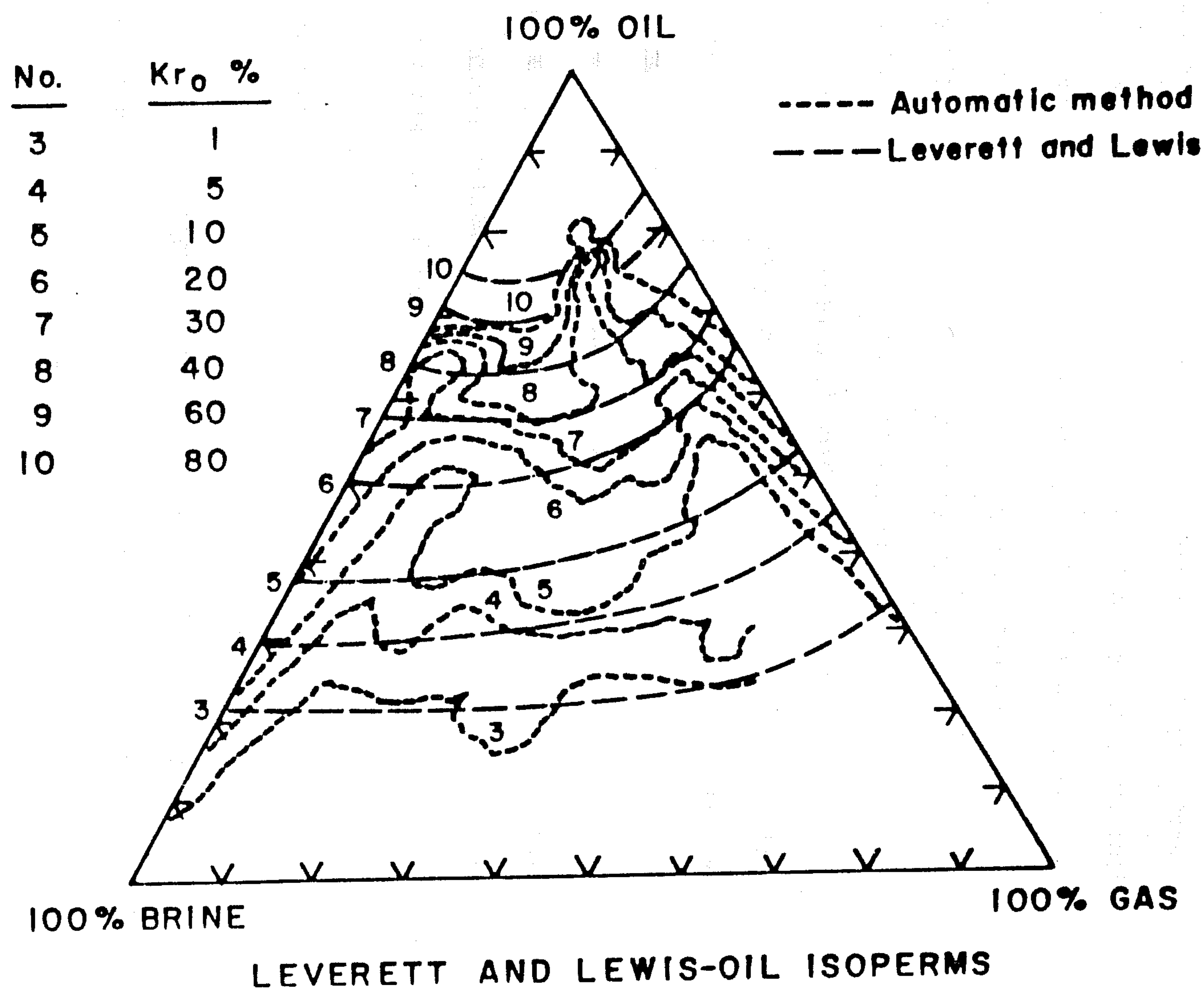

FIGURE 4. - Automatic method representation versus Leverett and Lewis data representation (oil isoperms).

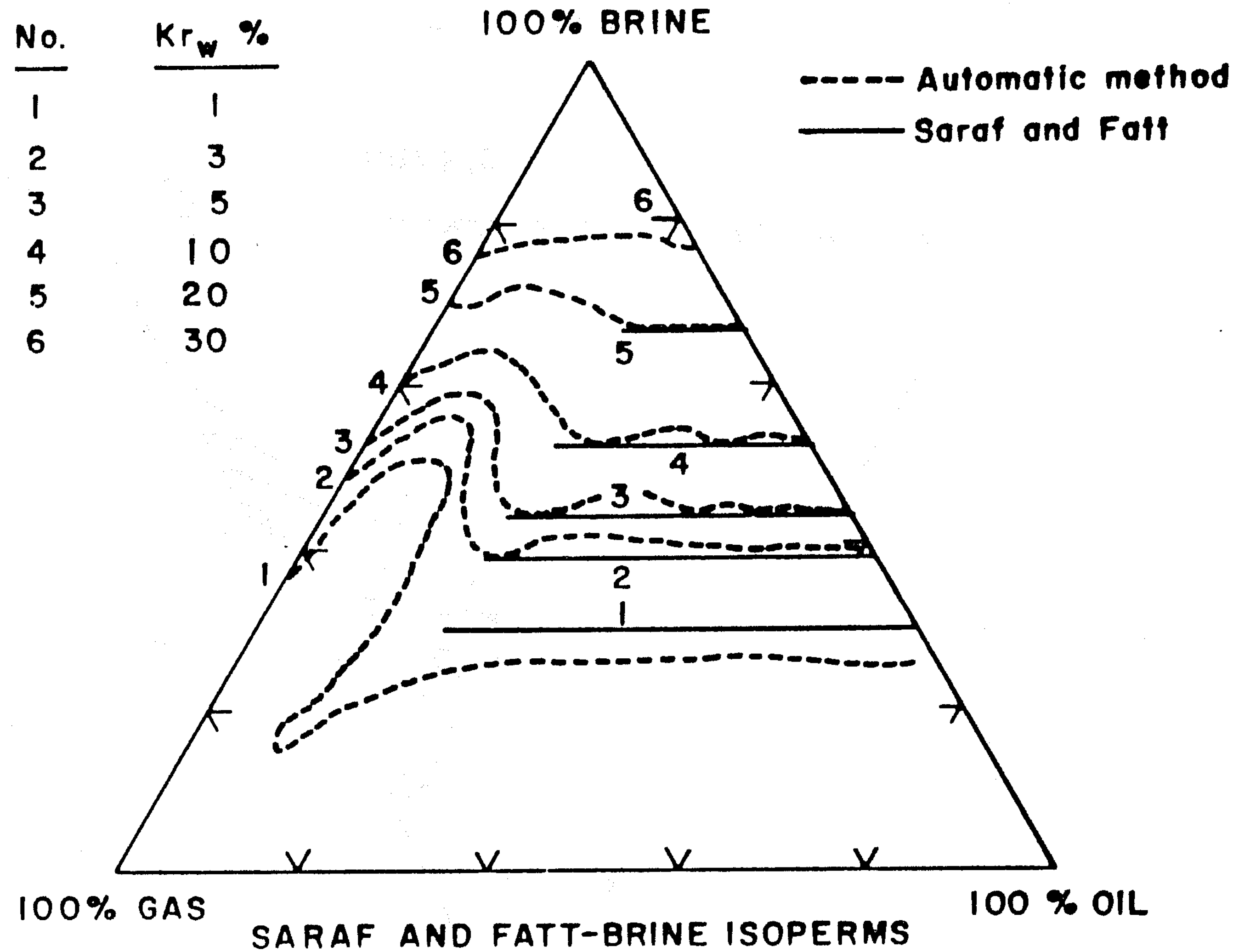

FIGURE 5. - Automatic method representation versus Leverett and Lewis data representation (water isoperms).

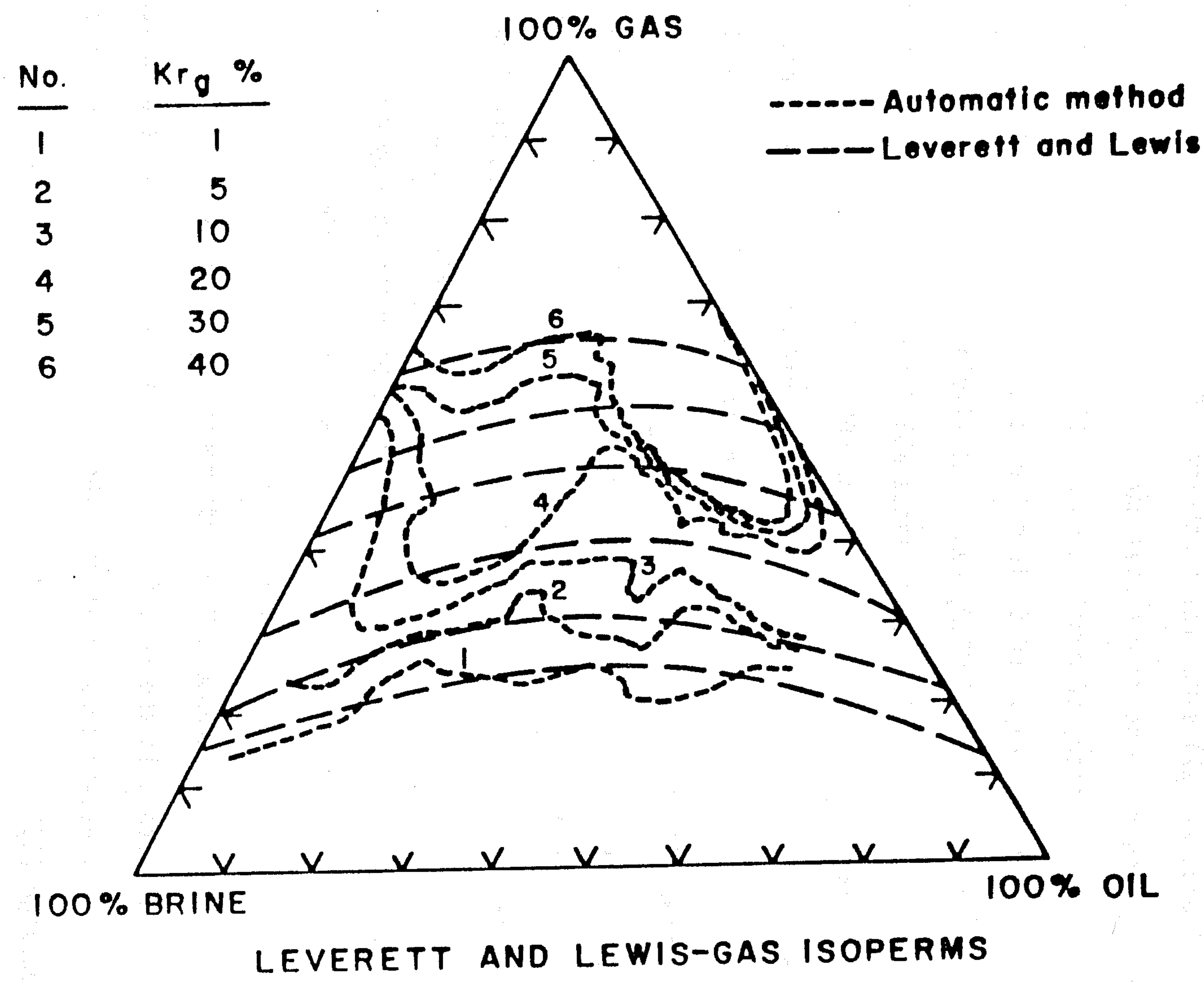

FIGURE 7. - Automatic method representation versus Leverett and Lewis data (gas isoperms).

program was written to print out the final relative permeability correlations when successful results were obtained, otherwise an error message should indicate where the problem occurred.

In addition to the modifications of the original BOAST program, several subprograms were also added. Their primary functions are explained in appendix A.

In addition to the original data file explained in the BOAST user's manual (17), a second data file is required to execute the program. Appendix B describes the input data for this new data file. There are two modifications to the original BOAST data file. If the option of using relative permeability correlations is chosen (IRELEQ greater than 0), only the capillary pressure tables should be read in instead of relative permeability and capillary pressure tables. Also, a grid pore volume modification data card should be read in after the porosity and permeability data card, in all cases.

The procedure to obtain the 18 parameters in the three-phase relative permeability function is as follows:

1. Run BOAST to obtain simulated fluid displacement data (fluid saturations as function of time) for an initial estimate of the parameters.

2. Compare saturations obtained from simulation with experimental data (estimate FUNC).

3. Run ZXSSQ to estimate a new set of parameters when fluid saturations do not agree within a specified tolerance.

4. Run BOAST again with the new set of parameters.

5. Steps 2 through 4 are repeated until the specified tolerance is achieved.

Preliminary results, using fluid-displacement laboratory data, show that the program converges within a reasonable amount of computer time. Although preliminary results show that the program works adequately, conclusions cannot

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12. ISML Library, Dec. 15, 1984, IMSL S-R051-9.2, Vol. 4.

13. Corey, A. T. The Interpretation Between Gas and Oil Relative Permeabilities. Producers Monthly, November 1957.

14. Naar, J. and J. H. Henderson. An Imbibition Model - Its Application to Flow Behavior and the Prediction of Oil Recovery. Soc. Pet. Eng. J., June 1961, p. 61.

APPENDIX A -- INPUT DATA GUIDE FOR MODIFIED VERSION OF BOAST

(This data file should be built as a separate input file to that of BOAST.)

Card #

1. Title Card (40A2)

2. Index for Relative Permeability data (I5)

   IRELEQ = 0   Relative permeability-saturation table used.

   = 1   Relative permeability correlations used

   (Skip the following data cards if IRELEQ = 0)

3. Title card (40A2).

4. Mobility index for oil, water and gas phase, respectively (3I5)

   MOBILO = 0 Oil phase immobile

   = 1 Oil phase mobile

   MOBILW = 0 Water phase immobile

   = 1 Water phase mobile

   MOBILG = 0 Gas phase immobile

   = 1 Gas phase mobile

5. Title card (40A2)

6. Parameters used in calling subroutine ZXSSQ (IMSL)(3I5,2F10.0,3I5,2F10.0 3I5)

NRES = Number of Residuals (or observations)

NPAR = Number of unknown parameters

NSIG = First convergence criterion. (See IMSL Manual for using subroutine ZXSSQ.)

EPS = Second convergence criterion. (See IMSL Manual for using subroutine ZXSSQ.)

16. Time tolerance for the calculated and laboratory results comparison. The calculated grid saturation (and/or pressure) values will be stored based on this input (F10.0).

(Skip the following data cards if IOPT not equal to 2.)

17. Title card (40A2)

18. Input vector of length 4 used only for IOPT equal to 2 (4F10.0)

PARM (1)

PARM (2)

PARM (3) (See manual for using subroutine ZXSSQ)

PARM (4)

6. Subroutine SATREL:

The calculated saturation and relative permeability values of oil, water, and gas are stored in this subroutine which is called by the subroutine TCOM.

7. Subroutine SSQMIN:

Calling program to ZXSSQ (IMSL) and updates the initial value of Marquardt parameter.

8. Subroutine FUNC:

A subprogram used for calculating the residual vectors. F(1), F(2), F(3),... for the given parameter values. P(1), P(2), P(3),...,P(18).